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How to obtain a bunch length of 50 μ in the CLIC main Linac.

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Abstract

The revised list of parameters of the CLIC study according to the scaling laws includes a very short rms bunch length of 50 μ in the main Linac for energies up to 1 TeV. This note presents a preliminary design of the bunch compressors based on RF pseudo rotators in the longitudinal phase plane requiring relatively low RF power and on standard magnetic chicanes. To achieve the high compression rate the first order analysis has been fully developed and optimised while magnetic high order effects and wakefields have been studied through a tracking program. Plots of the longitudinal phase plane simulation are shown which prove that the proposed Bunch Compressors are indeed able to provide a beam with such short bunch length while keeping high order effects at an acceptable level.

1 Introduction

The Damping Ring of the CLIC main Linac delivers a beam at the energy of 1.98 GeV, bunched at the RF frequency of 1.5 GHz with the following characteristics :

Bunch length (rms) $\sigma_z = 3.0$ mm
Relative energy spread (rms) $\sigma_E = \frac{\Delta E}{E_0} = 0.082$ %

This beam is transported through the main Injector Complex to reach the energy of 9 GeV at the entry of the main Linac, where it is accelerated at the RF frequency of 30 GHz. To minimize the effects of the high wakefields at that RF frequency, the length of the bunch should be reduced down to 50 μ as earlier as possible. Assuming adiabatic acceleration, the Liouville theorem for the longitudinal phase space provides the following relation between the bunch lengths $\sigma_{z,i}, \sigma_{z,f}$, the relative energy spreads $\sigma_{E,i}, \sigma_{E,f}$, the energies E_i, E_f, respectively at the exit of the Damping Ring (subscript i) and after the last Bunch Compressor (subscript f) :

$$\sigma_{z,i}\sigma_{E,i}E_i = \sigma_{z,f}\sigma_{E,f}E_f \tag{1.1}$$

From this we obtain $\sigma_{E,f} = 1.08$ % which is very close to the value of about 1 % required in order to prevent a significant increase of the beam transverse emittance in the main Linac [1]. We have chosen the well known $\frac{\pi}{2}$-type of bunch compression because its analytical model is quite simple at the first order and its hardware implementation relatively straightforward. Its principle is described in the section 2. Section 3 deals with the magnetic chicane while section 4 shows the results including those of the tracking program.

2 First order analytical model of the $\pi/2$-Bunch Compressor

Basically a $\pi/2$-Bunch Compressor consists of two pseudo rotations in the longitudinal phase space. The first one is obtained through an RF system working at an RF phase $\phi = k\pi$, which linearly correlates the relative momentum of a slice inside the bunch, with its distance from the centre. The head of the bunch gains energy and its tail loses it if k is odd. On the contrary the head loses energy and the tail gains it if k is even. The second pseudo rotation is achieved by a magnetic system which according to the sign of its parameter R_{56} forces high momentum slices of the bunch to travel longer ($R_{56} > 0$) or shorter paths ($R_{56} < 0$). The beam being ultra relativistic the speed of each slice is nearly the same and very close to the speed of light. Thus a slice which travels a longer path will be catched up by the other slices which travel shorter paths. Summarizing we see that, if R_{56} is positive and k odd or if R_{56} is negative and k even, the distance between the head and the tail of the bunch is reduced, leading to a compression of the bunch. In the other cases the bunch is stretched.
We have selected a magnetic chicane to get the required R_{56} for its simplicity and the availability of closed form expressions for its most important parameters. It will be treated in section 3. Its R_{56} being negative the phase of the RF system should be an even multiple of π. Let us assume that the RF frequency f_{RF} is much larger than $\frac{c}{2\pi\sigma_z}$ where c is the speed of light and that the beam distribution in the longitudinal phase space is a bidimensional Gaussian. The standard deviations of the bunch longitudinal coordinate and relative energy spread distributions are σ_z and $\sigma_{\Delta E/E}$ respectively. To simplify notations we will write σ_E instead of $\sigma_{\Delta E/E}$.
Then we obtain the following expressions for the RF voltage V and R_{56} [2]:

$$V = a\frac{\sigma_E}{\sigma_z}c_R\sqrt{1 - 1/c_R^2}$$
$$R_{56} = \frac{\sigma_z}{\sigma_E c_R}\sqrt{1 - 1/c_R^2}$$

where

$$a = \frac{Ec}{2\pi f_{RF}}$$

and $c_R = \frac{\sigma_{z,i}}{\sigma_{z,f}}$ is the compression rate. Assuming that $c_R^2 >> 1$ the expressions for V and R_{56} can be further simplified :

$$V = a\frac{\sigma_E}{\sigma_z}c_R$$
$$R_{56} = \frac{\sigma_z}{\sigma_E c_R}$$

We can convince ourselves quite easily that the required compression rate of 60 cannot be obtained by a single compression stage. In fact at the energy of 1.98 GeV the relative energy spread at the exit of the bunch compressor will be the relative energy spread at the entry multiplied by 60, i.e. 4.92 % (see 1.1). This value is too large for transporting the beam through the injector complex without losses. On the other hand at the energy of 9 GeV the R_{56} becomes 0.277 m which requires either a chicane with a large deflection and consequently high level of synchrotron radiation (both incoherent and coherent) or a too long chicane which implies very large maximum values of the β-functions.

Thus the Bunch Compressor has to be built in two stages. The expressions for the RF voltage and R_{56} for both stages are :

$$\begin{aligned} V_1 &= a_1 \frac{\sigma_E}{\sigma_z} c_{R,1} \sqrt{1 - 1/c_{R,1}^2} \\ R_{56,1} &= \frac{\sigma_z}{\sigma_E c_{R,1}} \sqrt{1 - 1/c_{R,1}^2} \\ V_2 &= a_1 \frac{\sigma_E}{\sigma_z} \frac{f_{RF,1}}{f_{RF,2}} c_R c_{R,1} \sqrt{1 - 1/c_{R,2}^2} \\ R_{56,2} &= \frac{\sigma_z}{\sigma_E} \frac{E_2}{E_1} \frac{1}{c_R c_{R,1}} \sqrt{1 - 1/c_{R,2}^2} \end{aligned} \tag{2.1}$$

where $a_1 = \frac{E_1 c}{2\pi f_{RF,1}}$ and $c_{R,i}$, $f_{RF,i}$, E_i are the compression rate, the RF frequency and the energy at the i-th stage respectively. Assuming that $c_{R,1}^2 >> 1$ and $c_{R,2}^2 >> 1$ these expressions can be further simplified :

$$\begin{aligned} V_1 &\approx a_1 \frac{\sigma_E}{\sigma_z} c_{R,1} \\ R_{56,1} &\approx \frac{\sigma_z}{\sigma_E c_{R,1}} \\ V_2 &\approx a_1 \frac{\sigma_E}{\sigma_z} \frac{f_{RF,1}}{f_{RF,2}} c_R c_{R,1} \\ R_{56,2} &\approx \frac{\sigma_z}{\sigma_E} \frac{E_2}{E_1} \frac{1}{c_R c_{R,1}} \end{aligned} \tag{2.2}$$

Installing the second stage in the Main Linac before the first accelerating structures we benefit from a larger RF frequency (30 GHz) which reduces the needed V_2. Inserting the numerical values of our case, we get :

$$\begin{aligned} V_1[MV] &\approx 17.2\, c_{R,1} \\ R_{56,1}[m] &\approx \frac{3.66}{c_{R,1}} \\ V_2[MV] &\approx 51.7\, c_{R,1} \\ R_{56,2}[m] &\approx \frac{0.28}{c_{R,1}} \end{aligned} \tag{2.3}$$

A compromise has to be found in order to have a reasonable $R_{56,2}$ while keeping V_1 in an achievable range. Typically R_{56} should be of the order of some centimetres. Choosing the value of 12 for $c_{R,1}$ we obtain from the expressions (2.1) :

$$\begin{aligned} V_1 &= 206\ MV \\ R_{56,1} &= 0.304\ m \\ V_2 &= 608\ MV \\ R_{56,2} &= 0.023\ m \end{aligned} \tag{2.4}$$

Let us mention here a small additional effect associated with the sine-wave of the RF system. Indeed, the finite length of the bunch generates a small distortion of the relative energy spread due to the subsequent acceleration. This effect should be evaluated because it will translate into a distortion of the longitudinal profile after the second compression. It is easy to see that the relative energy spread is modified by the acceleration according to the following expression ("banana effect") :

$$\sigma_{E,2}^2 = \sigma_{E,1}^2 + 2\sinh^2 \frac{\left(2\pi f_{RF}\sigma_z/c\right)^2}{2}$$

where $\sigma_{E,1}$ and $\sigma_{E,2}$ are the rms relative energy spreads before and after the acceleration respectively.

3 Optics of the chicane

The considered chicane is composed of three rectangular dipoles separated by two drifts of the same length L such that the lattice is geometrically symmetric about the middle point of the center dipole (see Figure 1). The bending angle of the center dipole is chosen to be twice that of each of the other dipoles. Thus the lattice is also symmetric from the optics point of view.

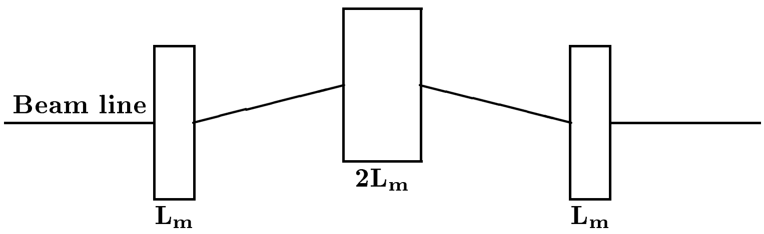

Figure 1: Chicane schematics

Let us split the center dipole into two rectangular dipoles of length L_m and deflection angle $-\theta$. The first and third rectangular dipoles can be seen as composed of a sector dipole of length $L_m = \theta/\rho$ and deflection angle θ and $-\theta$ respectively, followed by a defocusing wedge of normalised strength $\tan\theta/\rho$. The second and fourth dipoles can be considered as composed of a defocusing wedge of normalised strength $\tan\theta/\rho$ followed by a sector dipole of length L_m and deflection angle θ and $-\theta$ respectively. Their transfer matrices can easily be obtained [4] :

Transfer matrix of the first rectangular dipole :

$$M_1 = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ 0 & 1/\cos\theta & \tan\theta \\ 0 & 0 & 1 \end{pmatrix}$$

Transfer matrix of the second rectangular dipole :

$$M_2 = \begin{pmatrix} 1/\cos\theta & \rho\sin\theta & -\rho(1-\cos\theta) \\ 0 & \cos\theta & -\sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

Transfer matrix of the third rectangular dipole :

$$M_3 = \begin{pmatrix} \cos\theta & \rho\sin\theta & -\rho(1-\cos\theta) \\ 0 & 1/\cos\theta & -\tan\theta \\ 0 & 0 & 1 \end{pmatrix}$$

Transfer matrix of the fourth rectangular dipole :

$$M_4 = \begin{pmatrix} 1/\cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ 0 & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

Because of the double geometrical symmetry, first around the middle point of the drift and then around the middle point of the center dipole, the two-by-two transfer matrix of the chicane can be deduced [3] from the horizontal transfer matrix for the module composed of a sector dipole, a focusing wedge and half the drift :

$$\begin{aligned}\frac{D}{2}\cdot F\cdot B &= \begin{pmatrix}1 & \frac{L}{2}\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ \frac{\tan\theta}{\rho} & 1\end{pmatrix}\begin{pmatrix}\cos\theta & \rho\sin\theta\\ -\frac{\sin\theta}{\rho} & \cos\theta\end{pmatrix}\\ &= \begin{pmatrix}\cos\theta & \rho\sin\theta+\frac{L}{2\cos\theta}\\ 0 & \frac{1}{\cos\theta}\end{pmatrix}\end{aligned}$$

Thus we obtain [3] :

$$B\cdot F\cdot D\cdot F\cdot B = \begin{pmatrix}1 & 2\rho\tan\theta+\frac{L}{\cos^2\theta}\\ 0 & 1\end{pmatrix}$$

and finally the horizontal transfer matrix of the chicane M_h :

$$M_h = B\cdot F\cdot D\cdot F\cdot B\cdot B\cdot F\cdot D\cdot F\cdot B = \begin{pmatrix}1 & 4\rho\tan\theta+2\frac{L}{\cos^2\theta}\\ 0 & 1\end{pmatrix}$$

We remark that the chicane is optically equivalent to a drift of length l :

$$l = 2\left(2\rho\tan\theta+\frac{L}{\cos^2\theta}\right) = \frac{2}{\cos\theta}\left(2L_m+\frac{L}{\cos\theta}\right) > l_c \tag{3.1}$$

where $l_c = 4L_m + 2L$ is the chicane length. If we call β_i and β_f the values taken by the horizontal β-functions respectively at the entry and exit of the chicane, we get [4] :

$$\begin{aligned}\beta_f\beta_i &= \beta_i^2 - 2\alpha_i\beta_i l + (1+\alpha_i^2)l^2\\ &= l^2 + (\beta_i-\alpha_i l)^2\end{aligned}$$

Thus the product $\beta_i\beta_f$ is always larger than l^2 which implies that either β_i or β_f is larger than the chicane length. The matching to the rest of the lattice is much easier when we choose $\beta_f = \beta_i$ which imposes the following relation between α_i and β_i :

$$\beta_i = \frac{1+\alpha_i^2}{2\alpha_i}l \tag{3.2}$$

We remark that the symmetry of the horizontal β-function in the chicane can be achieved only if α_i is positive. The minimum value of the maximum β_i is obtained for $\alpha_i = 1$. We assume from now on that the expression (3.2) is fulfilled. Because also half the chicane behaves optically like a drift, the minimum of the horizontal β-function is obtained in the center of the chicane and it is given by :

$$\begin{aligned}\beta_{min} &= \beta_i - \frac{\alpha_i l}{2}\\ &= \frac{l}{2\alpha_i}\end{aligned}$$

The dispersion is of course symmetric around the middle point of the central dipole where it reaches its maximum. This can be obtained from the horizontal transfer matrix for the first half of the chicane :

$$M_2 \cdot D \cdot M_1 = \begin{pmatrix} 1 & 2\rho\tan\theta + \frac{L}{\cos^2\theta} & 2\rho\frac{1-\cos\theta}{\cos\theta} + \frac{L\tan\theta}{\cos\theta} \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3.3}$$

Thus assuming that the dispersion and its derivative are null at the entry of the chicane, the maximum dispersion is :

$$D_{max} = \frac{2}{\cos\theta}\left(L_m \tan\frac{\theta}{2} + L\tan\theta\right)$$

For small values of θ this can be approximated by $D_{max} \approx \theta(L_m + L)$. Similarly it is easy to obtain [5] :

$$R_{56} = -\left(4L_m\frac{\tan\theta - \theta}{\sin\theta} + 2L\tan^2\theta\right)$$

It is also possible to express the parameter R_{56} in terms of the chicane length l_c and of its equivalent length l (3.1):

$$R_{56} = -\left[l - l_c - 4L_m\left(\frac{\theta}{\sin\theta} - 1\right)\right] \tag{3.4}$$

For small values of θ we may write :

$$R_{56} \approx -2\theta^2\left(2L_m/3 + L\right)$$

It is interesting to note that the horizontal β-function at entry or exit of the chicane satisfy the following inequality obtained from (3.1) and (3.4) :

$$\beta_i > l_c - R_{56}$$

Finally expression (5) of [6] provides the growth of the normalised emittance in the chicane :

$$\Delta\gamma\epsilon_x[mm \cdot mrad] \approx 8.0\ 10^{-2} E^6 \frac{\theta^5}{L_m^2}\left[L + L_m + \frac{\beta_{min} + \beta_{max}}{3}\right]$$

4 Proposed Bunch Compressor

In section 1 we developed the motivation which compelled us to decide for a two stage Bunch Compressor, one at the energy of 1.98 GeV called from now on LEBC (Low Energy Bunch Compressor) and one at 9 GeV called from now on HEBC (High Energy Bunch Compressor). It was also shown that the compression rate of 12 for of LEBC was a good compromise. As a consequence its RF voltage and the value of its parameter R_{56} are (see 2.4) :

$$V_{LEBC} = 206\ MV$$
$$R_{56,LEBC} = -0.304\ m$$

The rms bunch length and the relative energy spread at the exit of LEBC are respectively $\sigma_z = 250\,\mu m$ and $\sigma_E = 0.98\ \%$. The maximum increase of the relative energy spread due to the finite length of the bunch during the acceleration from 1.98 GeV to 9 GeV is quite small ($\approx$ 0.001%). The RF voltage is provided by an RF system working at $f_{RF} = 1.50\ GHz$ and at zero RF phase. The parameter R_{56} is obtained by a chicane as described in the previous section consisting of three rectangular dipoles separated by a distance of 12.52 m. The first and third dipoles are each 4 m long while the second one is twice that length. The deflection angle θ is 100 mrad. The chicane is matched to a typical FODO lattice by a triplet at each side as shown in Figure 2. The growth of the normalised horizontal emittance is about 8.6 $10^{-5}\ mm \cdot mrad$, which has to be compared with the nominal value at the damping ring exit of 1.3 $mm \cdot mrad$ [7].

The HEBC is very similar to the LEBC apart from the higher energy and higher RF frequency. The required RF voltage will be provided by the Power Linac at 30 GHz with a zero RF phase and the R_{56} parameter is obtained by a chicane similar to that used in the LEBC, the corresponding values being (see 2.4) :

$$V_{HEBC} = 608\ MV$$
$$R_{56,HEBC} = -0.023\ m$$

The first and third dipoles are 6 m long while the second dipole is twice that length. The distance between the dipoles is 13.90 m. The deflection angle is only 25 mrad which causes a growth of the normalised horizontal emittance of 7.0 $10^{-4}\ mm \cdot mrad$ (to be again compared with 1.3 $mm \cdot mrad$ [7]). The chicane matched to a typical FODO lattice is shown in Figure 3.

The parameters of these two Bunch Compressors obtained at first order have been inserted into a tracking program to investigate how the beam will behave when higher order magnetic effects of the chicane and the strong wakefields are taken in account. Figure 4 shows the longitudinal phase space before the LEBC compressor (horizontal scatter plot), after the RF pseudo rotation (oblique scatter plot) and at the exit of the LEBC chicane (vertical scatter plot). Figure 5 shows the longitudinal phase space as the beam passes through the HEBC RF pseudo rotator (oblique scatter plot) and at the exit of the HEBC chicane (vertical scatter plot). Finally Figure 6 shows the longitudinal profile of the beam after compression.

5 Conclusion

This note presents the preliminary design of a Bunch Compressor for the CLIC main Linac which succeeds in compressing the beam down to $50\,\mu m$. The tracking shows that the high order effects are small, lengthening the bunch slightly to $51\,\mu m$. Moreover a first calculation of the effect of a 10 % error on the initial bunch length at the exit of the Damping Ring will only cause a jitter of the relative energy spread in the main Linac of the order of 0.1 %.

The following table shows the parameter list for both stages of the CLIC main Linac Bunch Compressor:

Parameter	Unit	1st Stage	2nd Stage
Energy	GeV	1.98	9
RF voltage	MV	206	608
RF frequency	GHz	1.5	30
Chicane length	m	41.05	52.21
Chicane Deflection angle	$mrad$	100	25
Chicane Bending Field	T	0.165	0.125
Chicane radius of curvature	m	40	240
R56	m	-0.304	-0.023
Compression rate		12	5
Bunch length at entrance (σ_z)	mm	3	0.25
Bunch length at exit (σ_z)	mm	0.25	0.050
Energy spread at entrance ($\sigma_{\Delta E/E}$)	%	0.082	0.22
Energy spread at exit	%	0.98	1.08
Hor. emittance growth	$mm \cdot mrad$	$8.6\,10^{-5}$	$7.0\,10^{-4}$

References

[1] D. Schulte, Private communication .

[2] G. Guignard, T. E. d'Amico, 'Preliminary Design of a Bunch Compressor for CLIC', Proc. Europ. Part. Acc. Conf. 94, London, June 1994.

[3] T. E. d'Amico, G. Guignard, 'First-order design of a new type of isochronous arc', CERN SL/95-120, 1997.

[4] P.J. Bryant and K. Johnsen, 'The Principles of Circular Accelerators and Storage Rings', Cambridge University Press, 1993.

[5] F. Chautard, L. Rinolfi, 'Bunch Compressor for the CLIC Test Facility', CLIC Note 240, August 1994.

[6] T.O. Raubenheimer, P. Emma, S. Kheifets, 'Chicane and Wiggler Based Bunch Compressors for Future Linear Colliders', SLAC-PUB-6119, May 1993.

[7] L. Rinolfi, 'A CLIC Injector Complex for the Main Beams', CLIC Note 354.

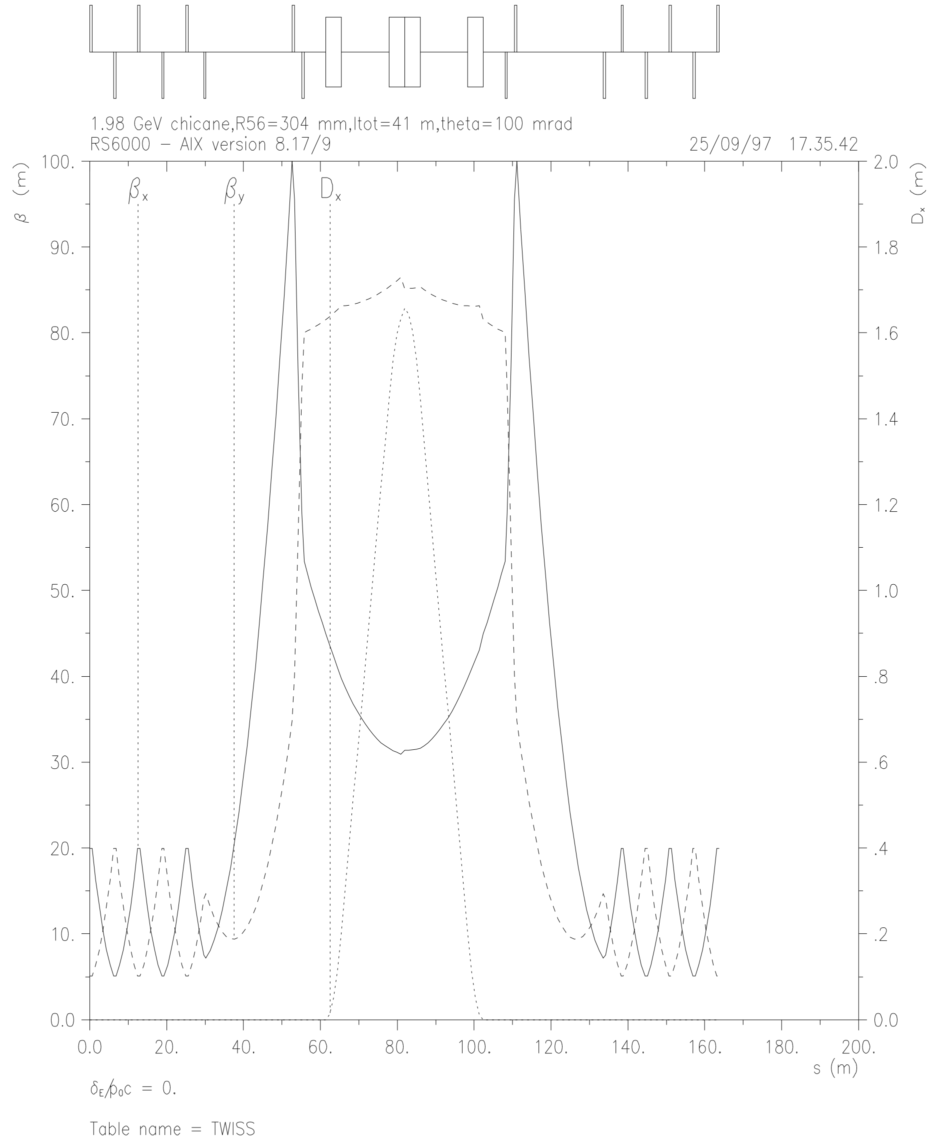

Figure 2: Optics of the LEBC chicane

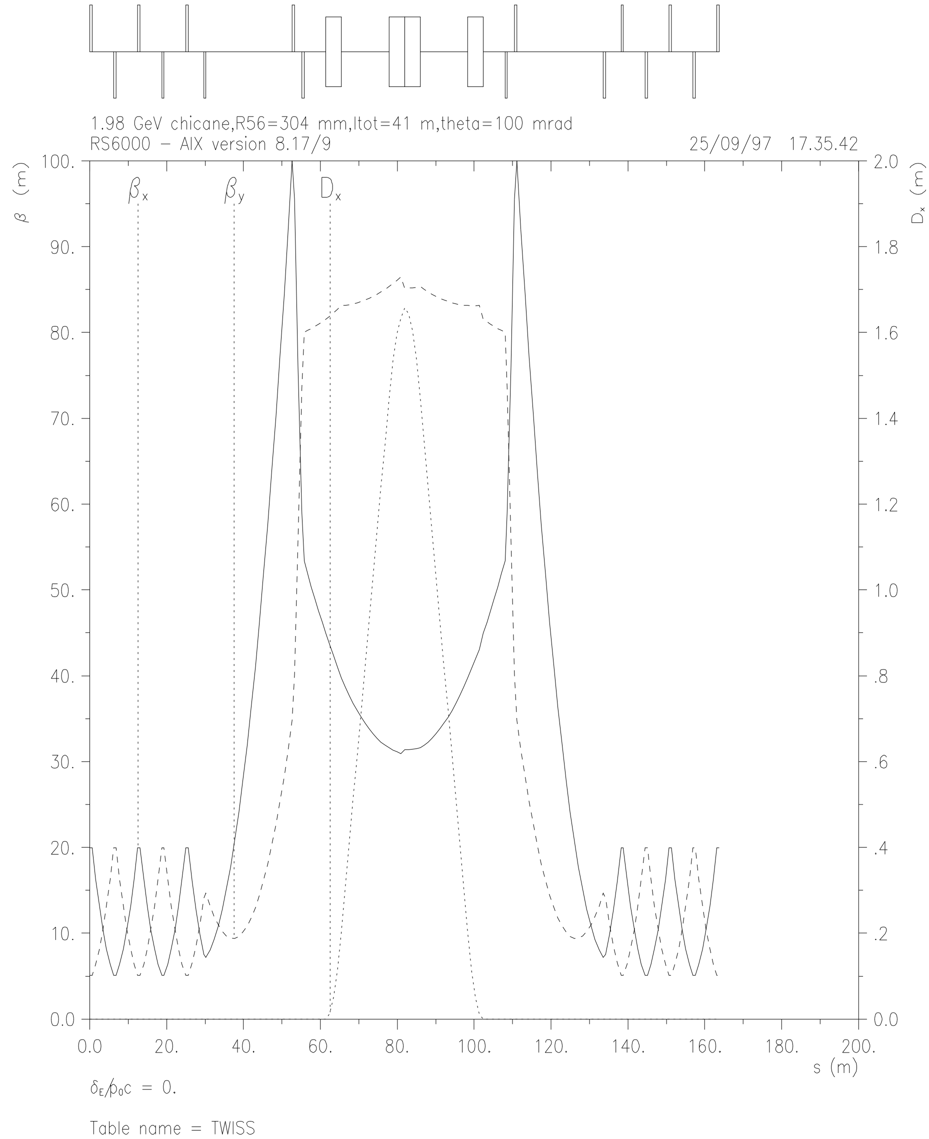

Figure 3: Optics of the HEBC chicane

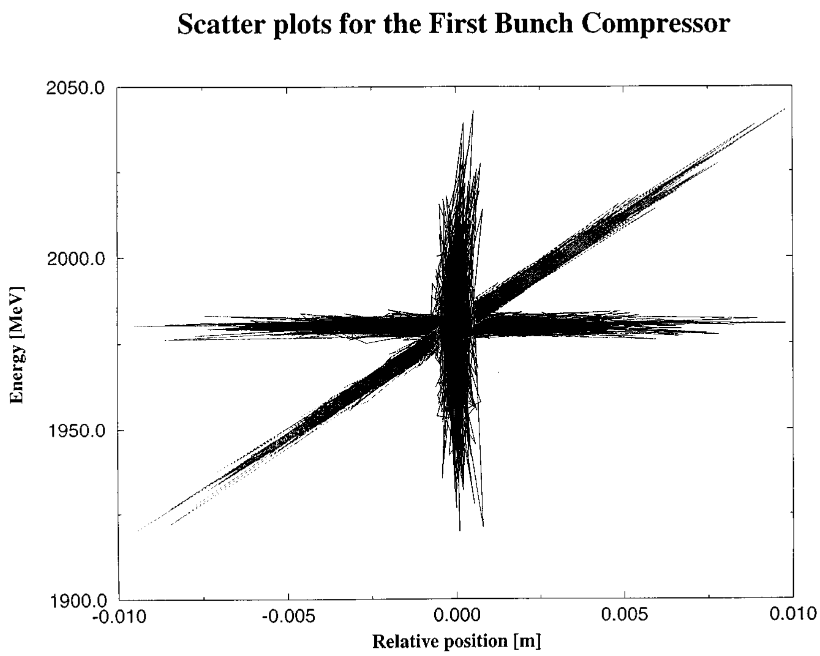

Figure 4: Longitudinal phase space during first bunch compression

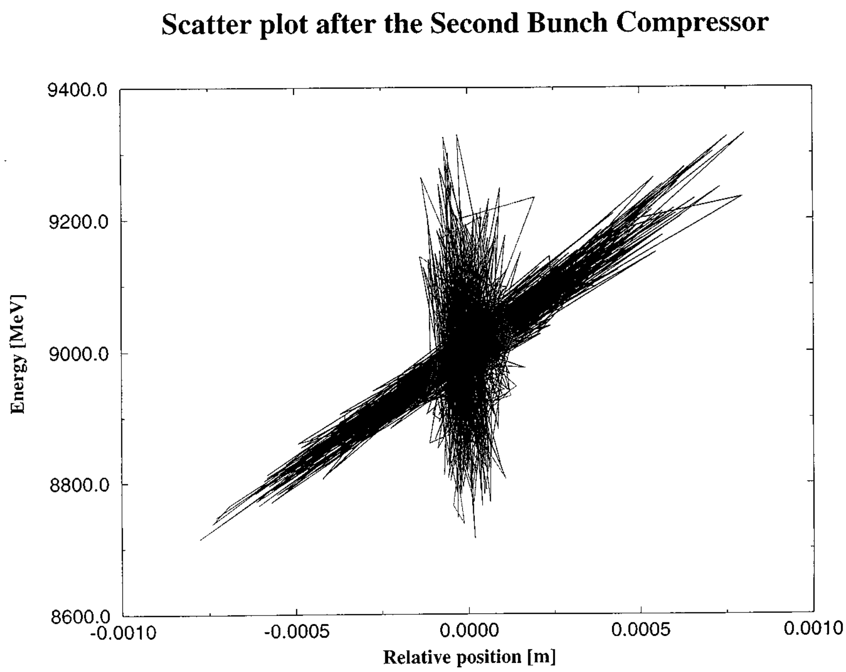

Figure 5: Longitudinal phase space during second bunch compression

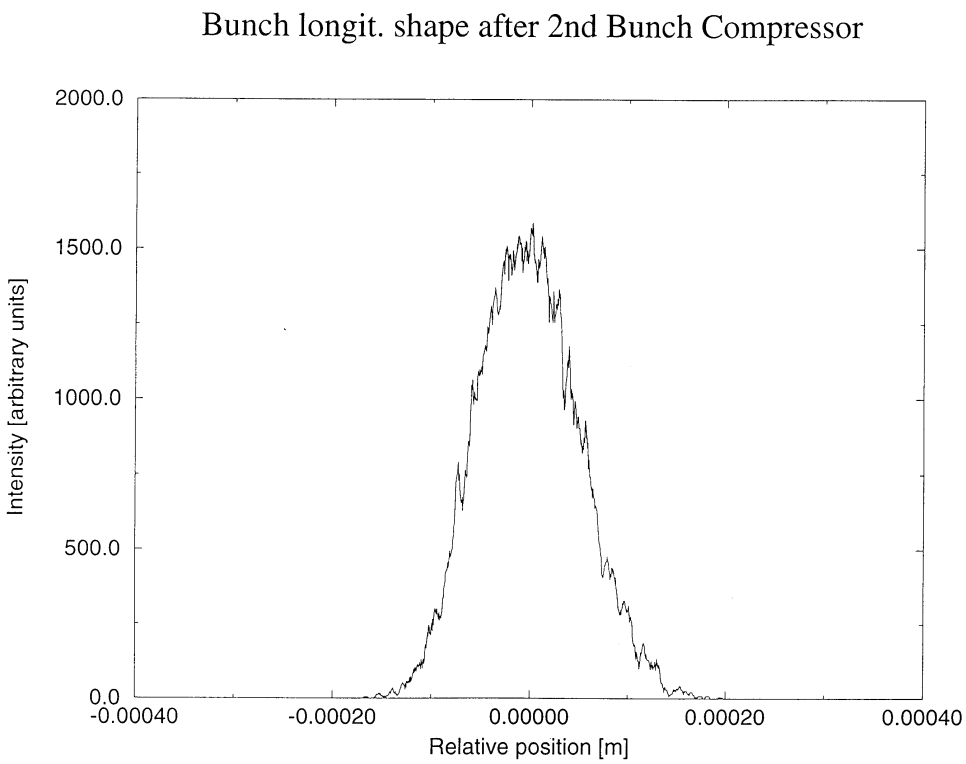

Figure 6: Bunch longitudinal profile